

**The State Research Center of Russian Federation
TROITSK INSTITUTE FOR INNOVATION & FUSION RESEARCH
(SRC RF TRINITI)**

High power EUV DPP light source

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Introduction

First EUV source at TRINITI was built **10 years ago !**

This source was based on pinch discharge in Xe and generated about 1 W EUV in band power in 2 p.

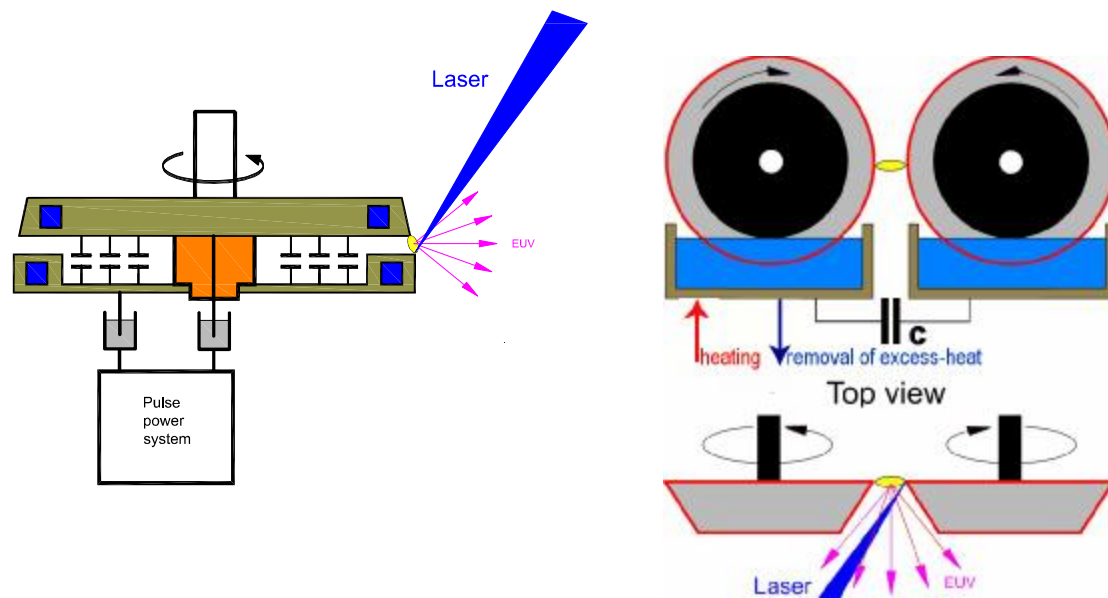
What we have now?

In this presentation we discuss EUV light characteristics of three EUV DPP sources developed at TRINITI last years. These EUV sources are based on pinch discharge in tin vapour between rotating disk electrodes.

Using obtained characteristics an attempt to estimate the possibilities to develop high power EUV DPP light source required for HVM tool will be done.

Main discharge produce plasma (DPP) systems as EUV sources

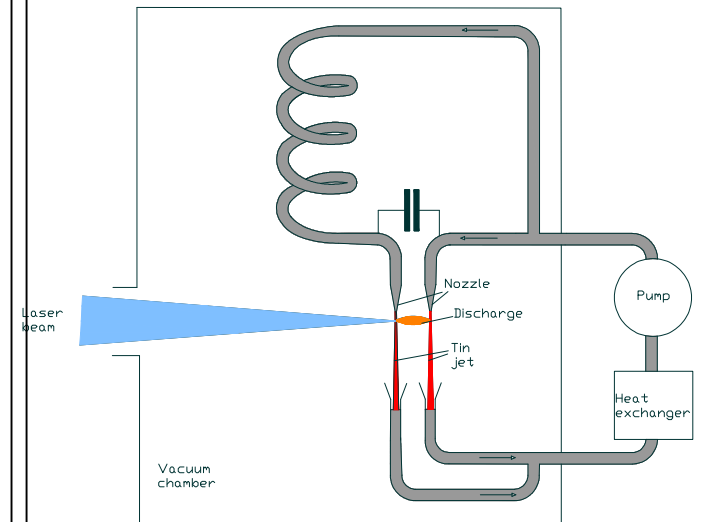
Concept 1 : Discharge between rotating disk electrodes (RDE) that are covered with Sn layer



Design 1

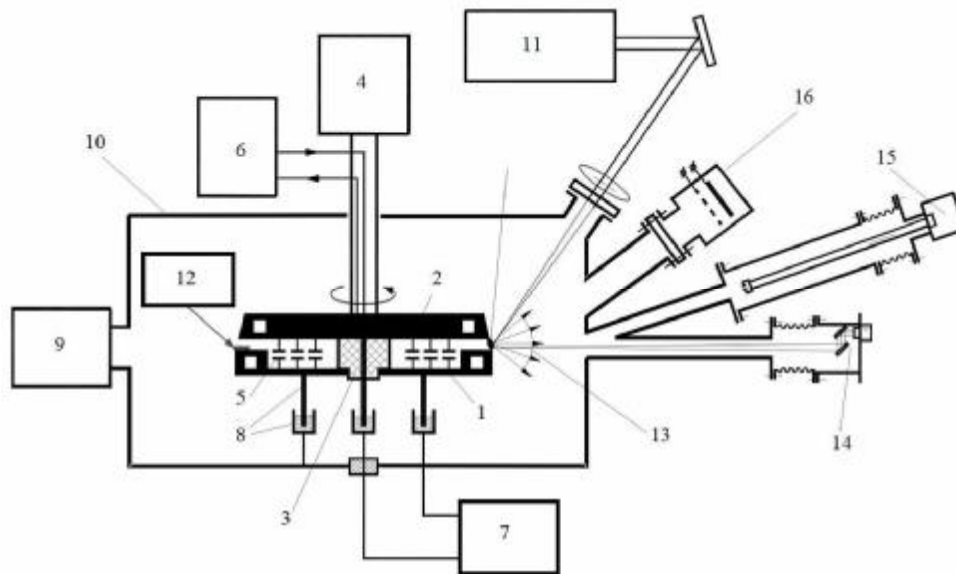
Design 2

Concept 2: Discharge between two liquid metal (Sn) jet electrodes



Design 3

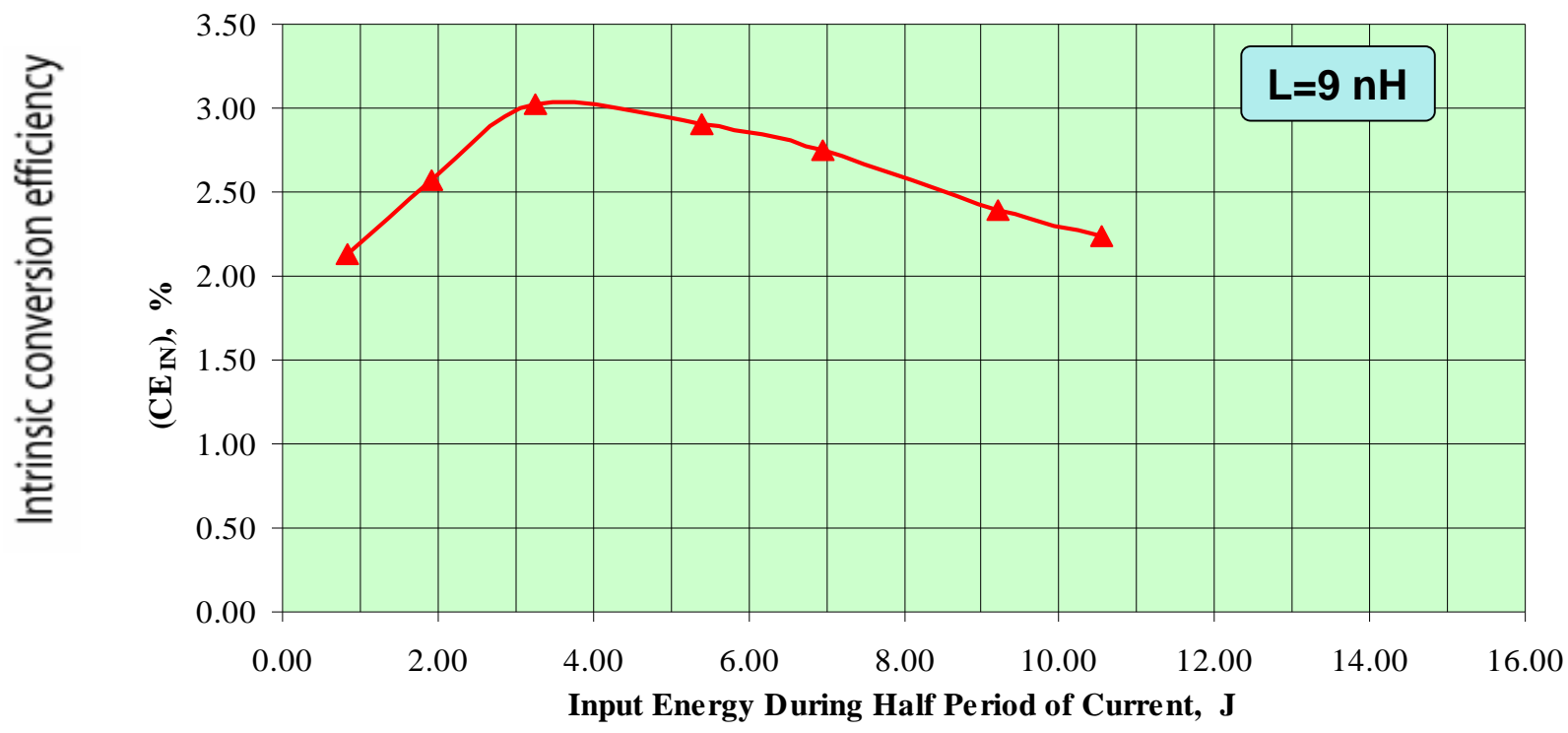
Sn RDE source design 1



1- cathode, 2- anode, 3- insulator, 4- electric motor, 5- capacitor bank, 6- cooling system, 7- pulsed power supply, 8- sliding contacts, 9- turbomolecular pump, 10- vacuum chamber, 11- laser, 12- tin regeneration system, 13- EUV radiation, 14- system for measuring the eUV energy and power, 15- pinhole camera for recording EUV images of the plasma, 16- Faraday cup, 17- discharge

Sn RDE source design 1

Intrinsic conversion efficiency as a function of energy put into the plasma during first half period of the current obtained at 10 Hz with XeF laser



Continuous source operation

EUV power 276 W/2p at input power 15.6 kW (5.2 J x 3 kHz)

or

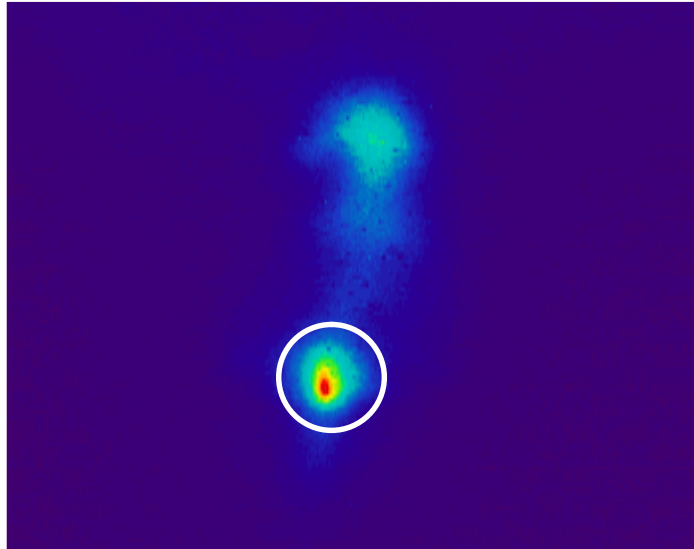
EUV power 270 W/2p at input power 19.8 kW (9.9 J x 2 kHz)

See: Int.Symposium on EUV Lithography, 2008 Lake Tahoe, CA



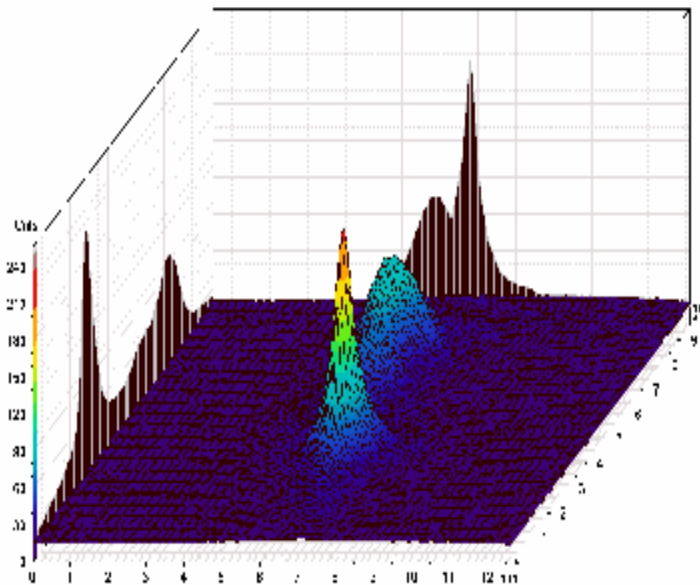
Discharge in tin vapour between RDE. Design 1.

Collection efficiency

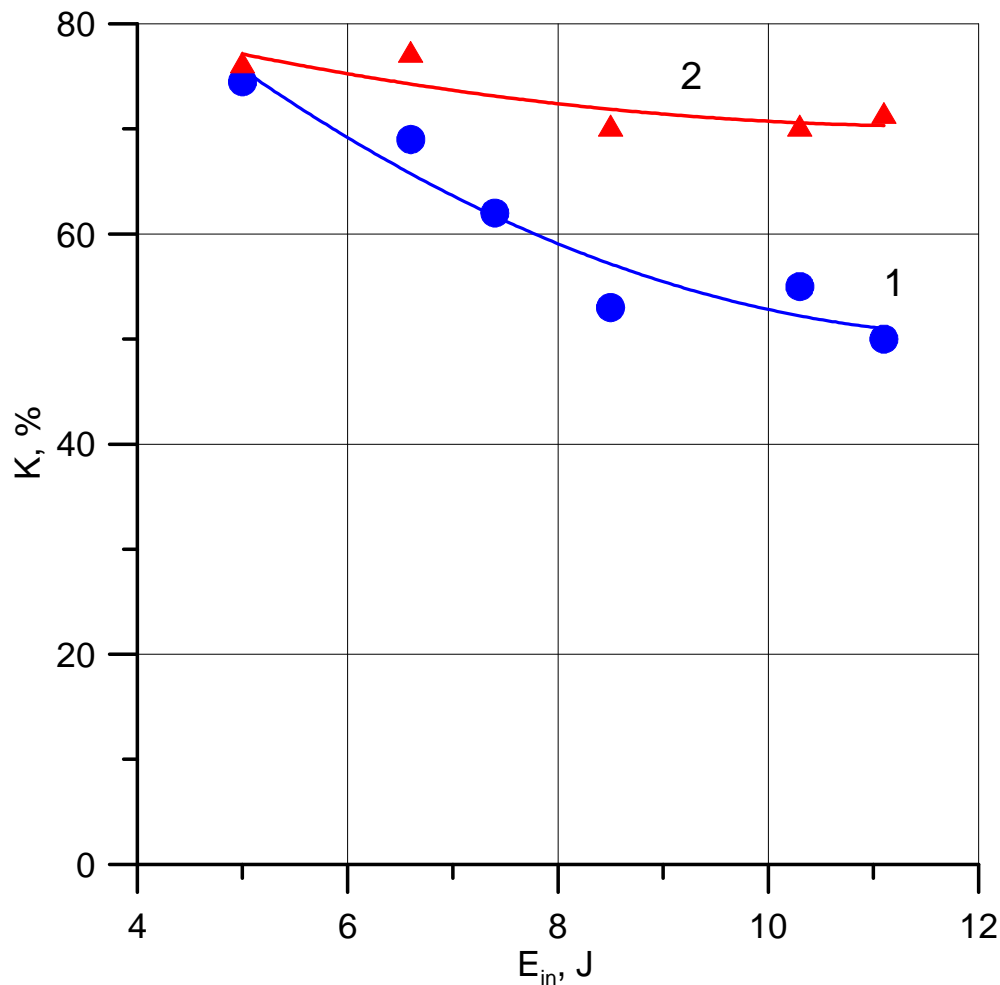


Only EUV light emitted by small plasma volume can be collected.

Collection efficiency **K%** was estimated on the measured distributions of EUV radiation with the CCD-camera as the relation of EUV energy into a circle with diameter 1 mm to EUV energy on all field of the CCD-camera (background emission).



Collection efficiency using pre-pulse

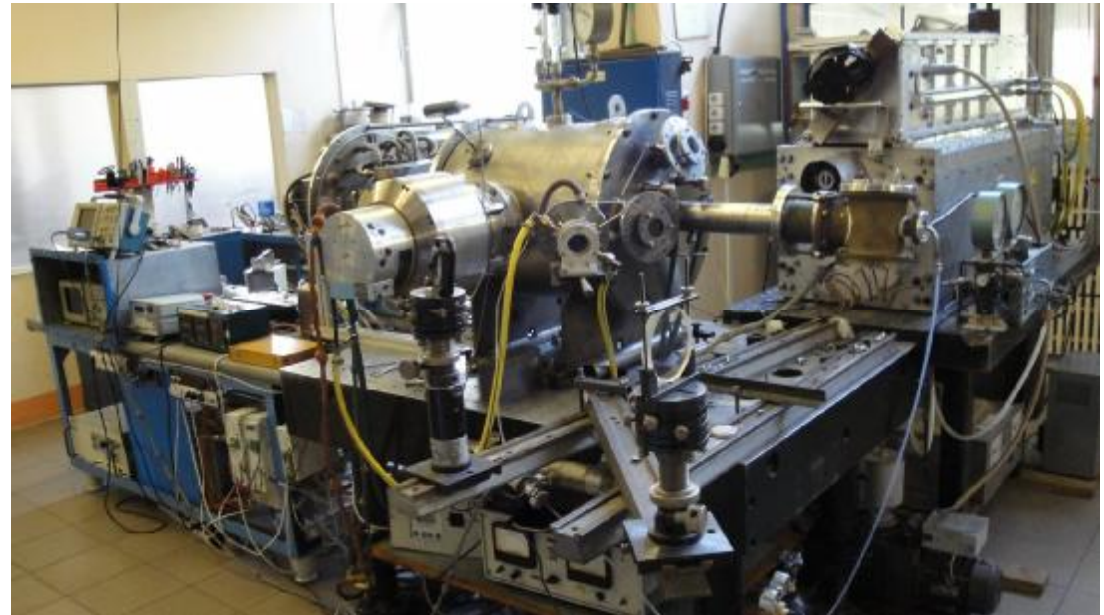
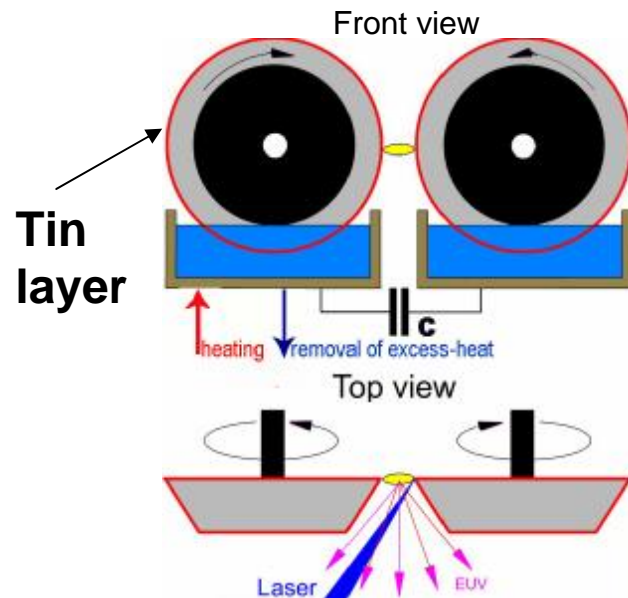


Using pre-pulse as small current through discharge gap before high current breakdown makes possible to increase collection efficiency K up to 70% at high input energy (6-11 J)

Dependences of collection efficiency on input energy in excitation circuit without pre-pulse (1) and with pre-pulse (2).

Sn RDE source design 2

First generation

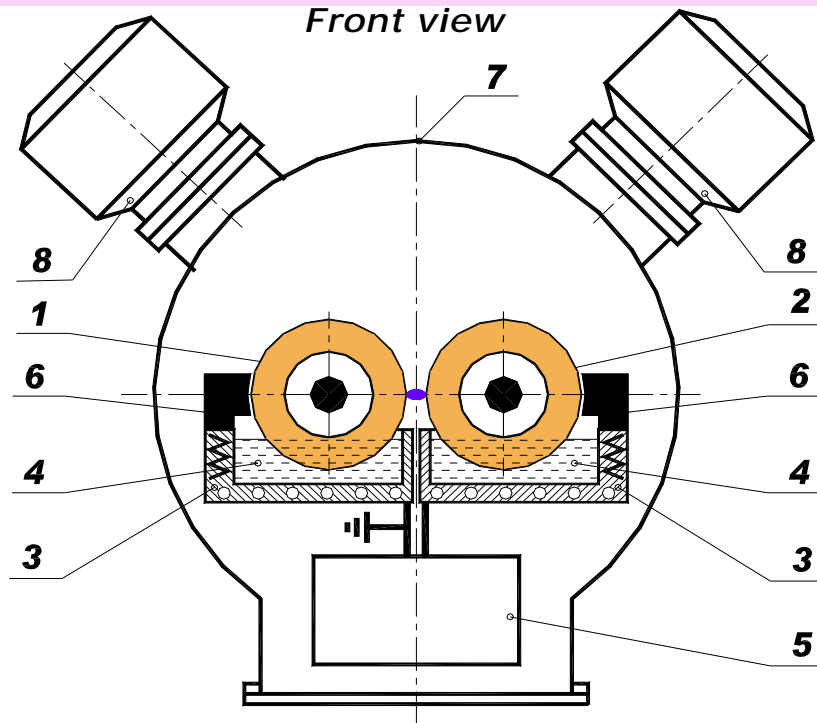


Electrical circuit without pre-pulse.

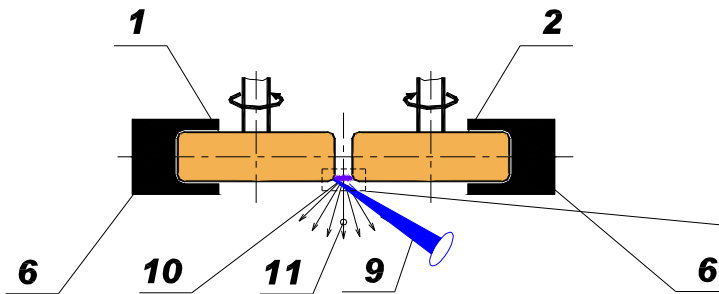
Input power 13.2 kW (3.4 J x 4 kHz)

CE= 1.3% - 1.8% depended on tin layer thickness
and other discharge conditions

Sn RDE source design 2

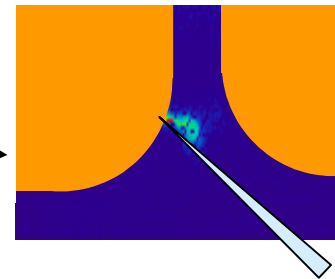


Top view of electrode configuration

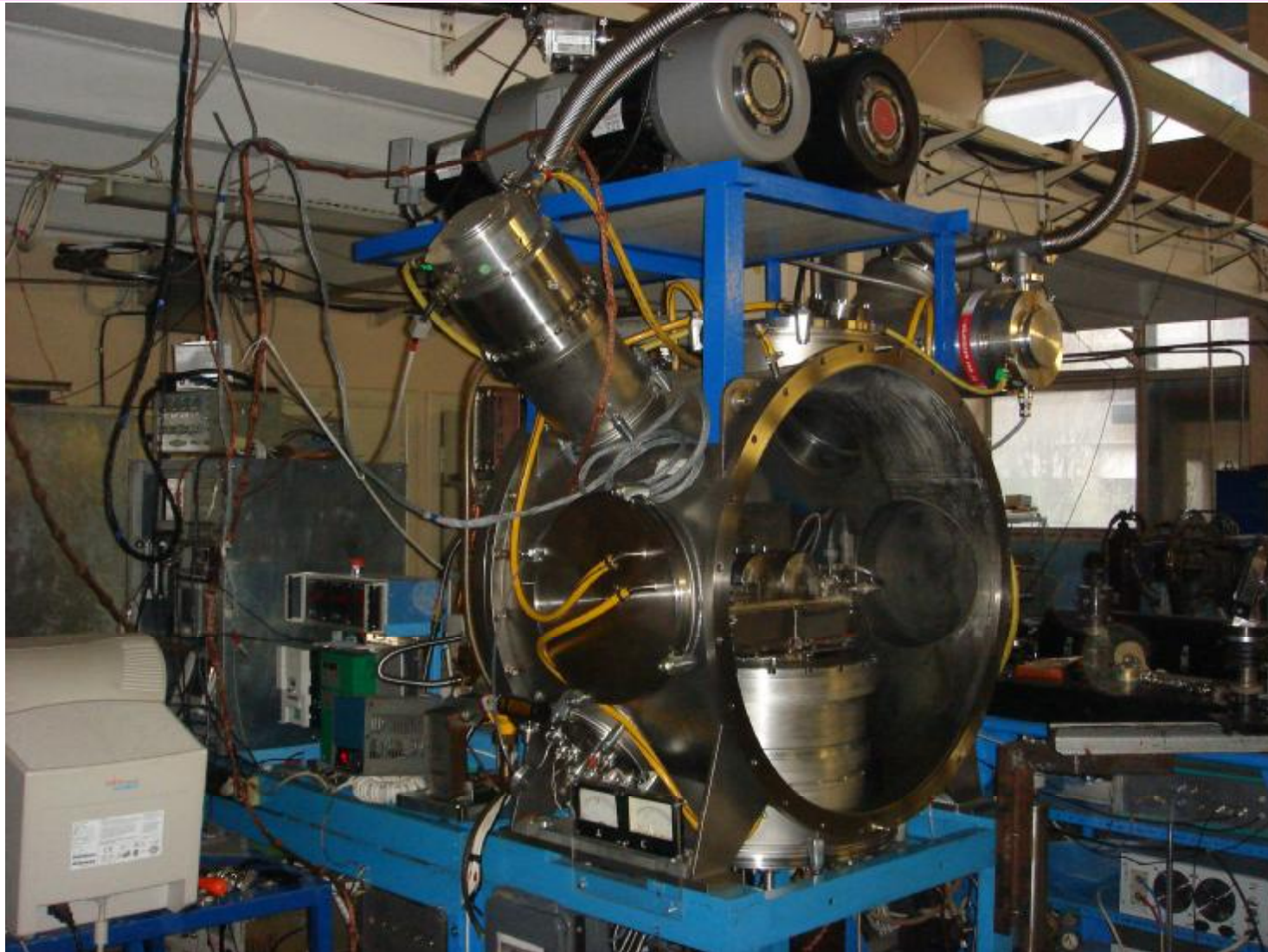


Second generation of Sn RDE source was designed to achieve EUV power ~ 3 kW with input power ~ 200 kW at pulse repetition frequency 20-30 kHz

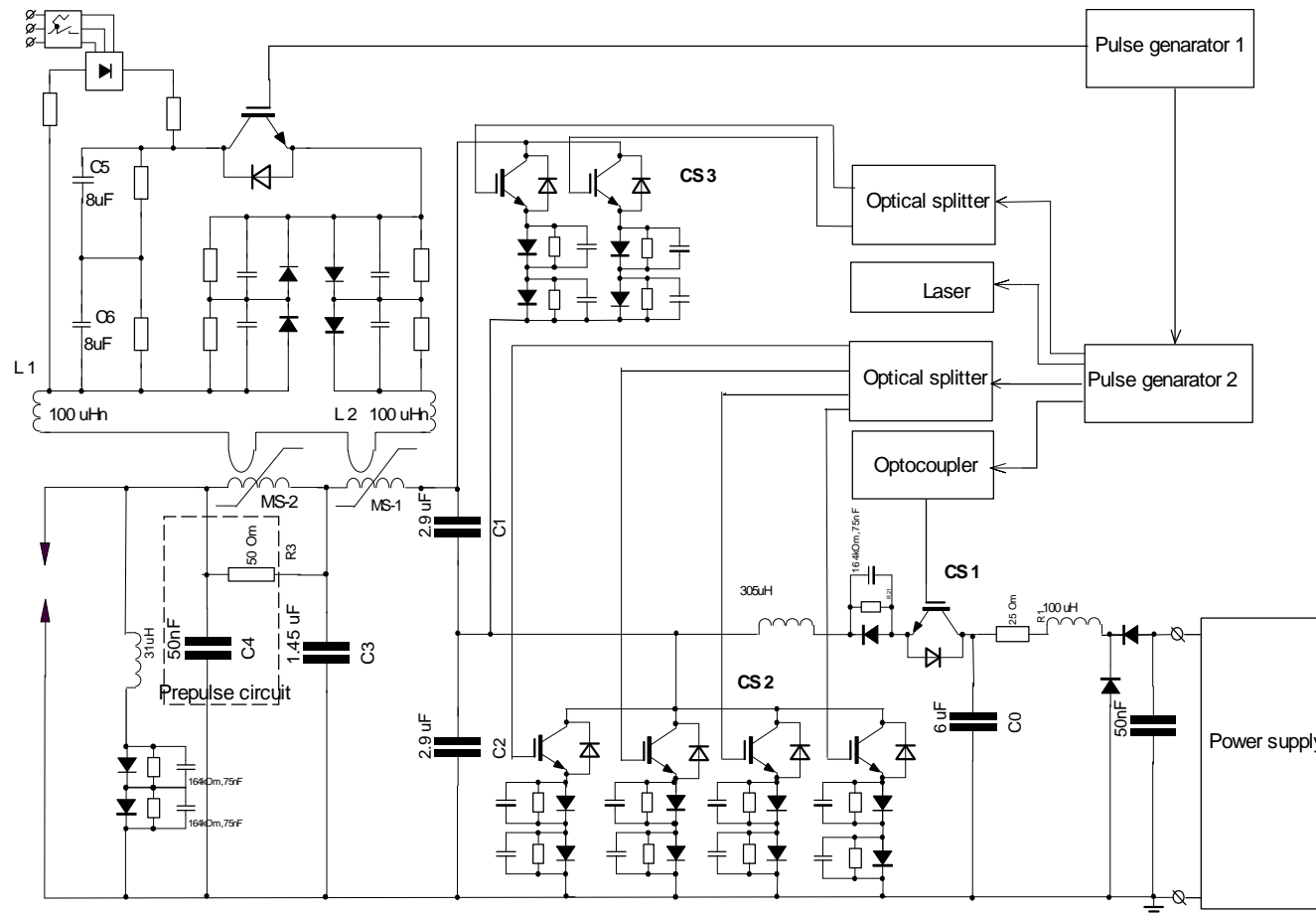
- 1- rotating electrode on which focus laser beam;
- 2 - second rotating electrode;
- 3 - body of bathes;
- 4 - liquid tin;
- 5 - pulse power system;
- 6 - regulation of tin layer;
- 7 - vacuum chamber;
- 8 - turbo-vacuum pump;
- 9 - laser beam position;
- 10 - discharge plasma;
- 11 - EUV radiation



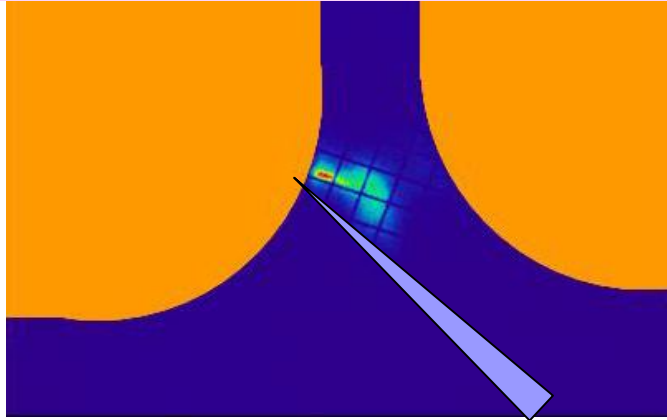
Sn RDE source design 2



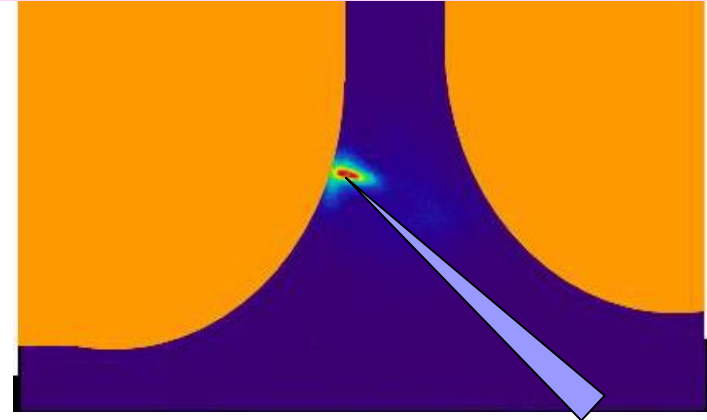
Discharge excitation circuit with pre-pulse and recuperation



Sn RDE source design 2



***Image of the plasma.
Laser beam was focused on
the cathod. $E_{in}=8.5$ J, Zr filter***



***Image of the plasma.
Laser beam was focused on
the anod. $E_{in}=8.5$ J, Be filter***

An analysis of the images of EUV-emitting plasma, revealed the following: under typical discharge conditions the plasma regions with characteristic sizes of ~ 1 mm, which are an efficient EUV source, arise near the electrode onto which the laser beam is focused.

In other words, the conditions for discharge pinching arise in the region of the interelectrode gap where the initial plasma cloud is formed.

In our opinion, this fact is nontrivial. To understand this phenomena and other effects we carried out simulation of the discharge and EUV emission in the band 13.5 ± 0.135 nm.

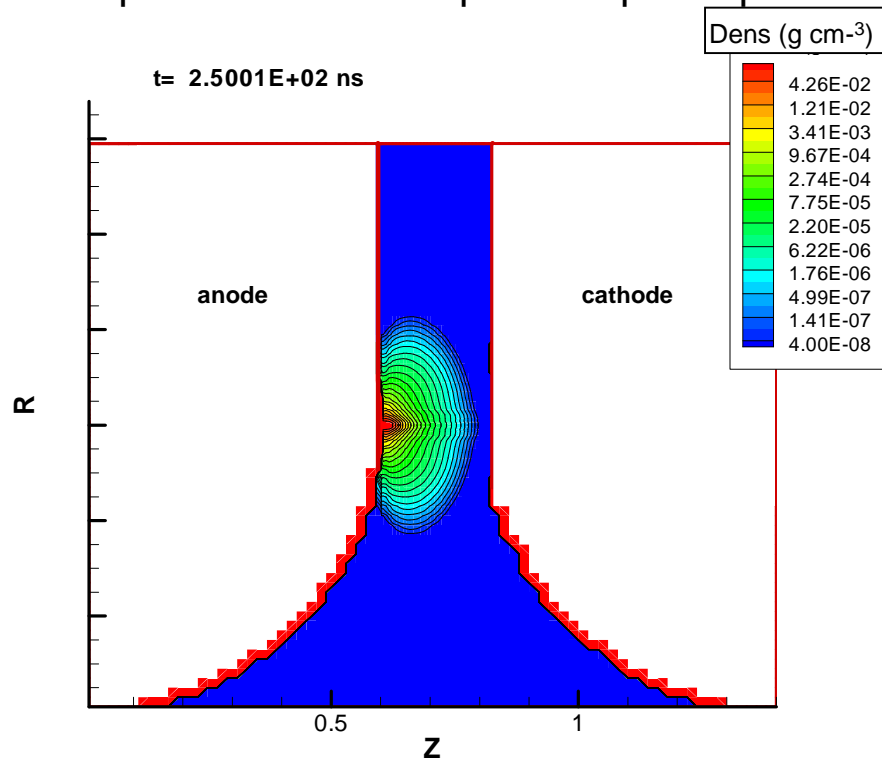
Results of computer simulation of discharge and generation of EUV radiation

The laser-ignited discharge was simulated using the 3D version of radiation-magnetohydrodynamic (RMHD) code, developed based on the 2D RMHD ZETA code, with the laser pulse and electric parameters of the pulse power supply system similar to the experimental-setup parameters and electrode geometry.

The 3D version of the ZETA code includes two- temperature (electron and ion temperatures) magnetohydrodynamic model* with multigroup radiation transport.

Results of computer simulation

For the laser beam focused on the anode the calculation was performed in two stages. The ablation and spread of molten tin layer under Nd:YAG laser irradiation were calculated in the first stage. Under a laser pulse a liquid tin layer is heated and evaporated to form a plasma cloud. The maximum plasma electron temperature $T_e = 3.2$ eV is obtained near the critical-density surface. During the plasma spread the temperature decreases due to the plasma expansion. An example of vapour spread dynamics is shown in figure.



Dynamics tin vapor spread under laser pulse irradiation of the anode covered with molted tin. The mass-density isolines correspond to 250 ns

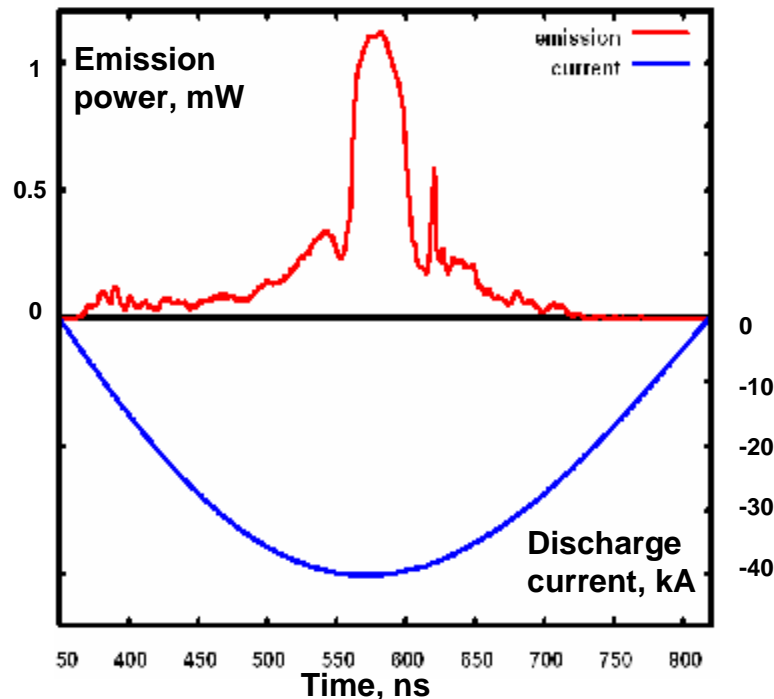
Approximately through 135 ns after a maximum of a laser pulse (250 ns of a calculation time) tin vapors reach an opposite electrode.

Though to 250 ns tin vapor have achieved an opposite electrode (cathode in this variant) their temperature and conductance is too low and the discharge is not fired.

However after collision of vapors with a solid surface of the cathode towards to a stream of tin vapors the shock wave is spread, in which tin vapors stop and are heated again, a degree of plasma ionization and its conductance increase.

Pulse of EUV radiation from the discharge (above) and dynamics of a current in the discharge (below)

$$\lambda = 13.5 \pm 0.135 \text{ nm}$$

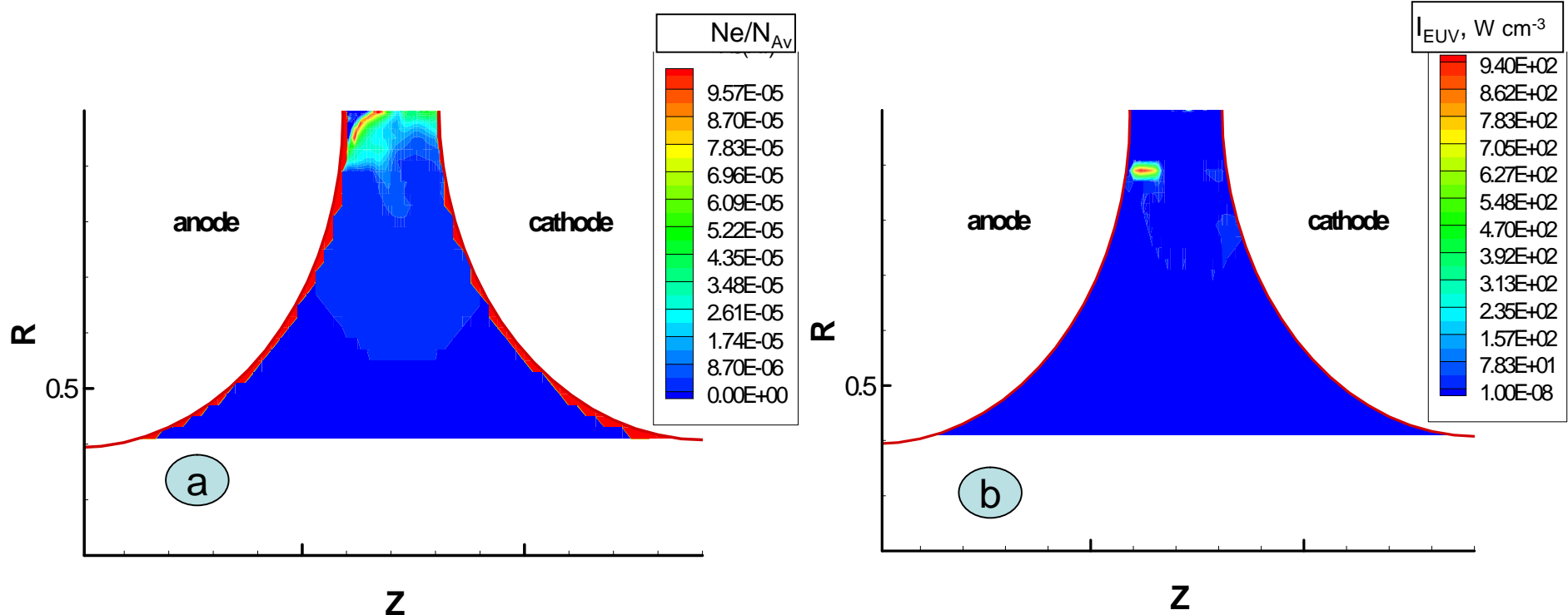


Beginning with the instant since of plasma arrival at the cathode, the computation passed to the second stage, including calculation of the electromagnetic field with a boundary condition corresponding to an external LRC circuit with $L = 13.5 \text{ nH}$, $R = 0$ and capacitance $C = 1.45 \text{ }\mu\text{F}$, charged at the initial instant to a voltage $U = 4 \text{ kV}$.

By the instant $T = 350 \text{ ns}$ the plasma conductivity becomes sufficient for discharge to develop, and a current through the plasma rapidly increases, which heats the plasma due to the Joule dissipation. The discharge current dynamics is shown in figure (blue). The discharge current increases to 40 kA by the instant $T = 570 \text{ ns}$.

. The plasma is heated by the discharge current and is compressed by the pressure of the current magnetic field. With an increase in the plasma temperature and density, the intensity of emission from the plasma, in particular, in the spectral band $13.5 \pm 0.135 \text{ nm}$, increases as well. The calculated EUV pulse in this spectral range from a discharge of specified geometry is shown in figure (red) The radiation power reaches a maximum (1.1 MW) at $T = 581 \text{ ns}$.

Distribution of plasma density at the moment of a maximum of EUV radiation (a) and distribution of EUV radiation density in the discharge (b) in moment 581 ns (maximum of radiation)

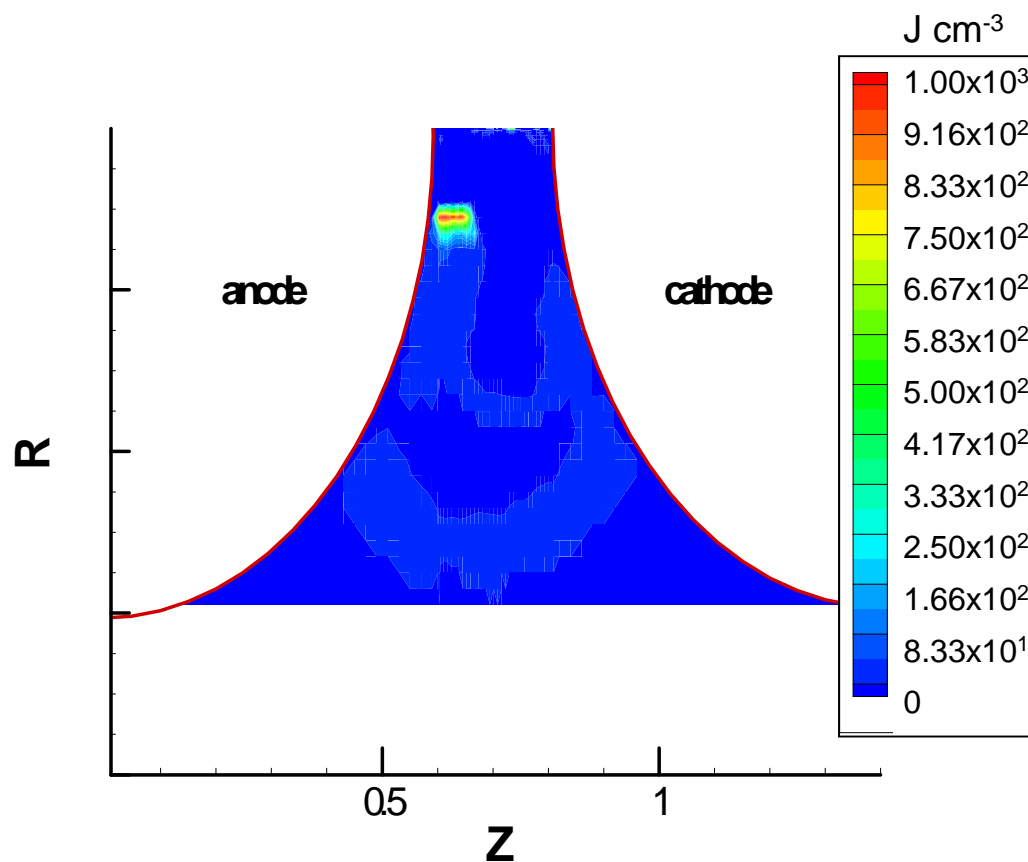


In a point maximum EUV densities the parameters of plasma have following of quantities: temperature of electrons $T_e=18,3\text{eV}$, integrated electron density $Ne=1.6\cdot 10^{18}\text{ cm}^{-3}$, medial degree of plasma ionization of tin $\langle Z \rangle = 7.4$.

The point of greatest density of EUV radiation does not agree with a point of a laser radiation focus on the anode. With diminution of a current EUV density promptly decreases. Integrated on time the radiation energy in a band $13.5\pm 0.135\text{ nm}$ was calculated as $0.12\text{ J}/2\pi$, it is a little bit less experimentally measured ($0.18\text{ J}/2\pi$).

Distribution of integrated on time EUV radiation ($\lambda=13.5\pm0.135$ nm) density

The basic area of EUV radiation in this variant of calculation allocates near the anode surface, it integrated on time the size is $0.75\times0.5\times 0.6$ mm³.



The point of formation of the main EUV emission region (either near the anode or near the cathode) in the case of anode ablation by laser radiation and subsequent compression by the discharge magnetic field is primarily determined by the plasma mass distribution. The linear plasma mass generally decreases at a free expansion of the plasma torch if the distance from the center along the compression axis increases. If the compression occurred immediately at the instant of plasma arrival at the cathode, a pinch would form near the cathode. However, as was noted above, the discharge develops much later, when the shock wave, being reflected from the cathode, passes a significant part of the interelectrode gap. The plasma is most rapidly compressed near the anode, where the main pinch arises.

Sn RDE source design 2

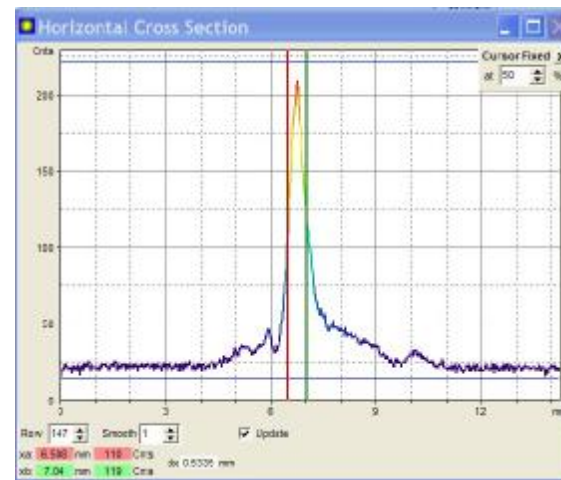
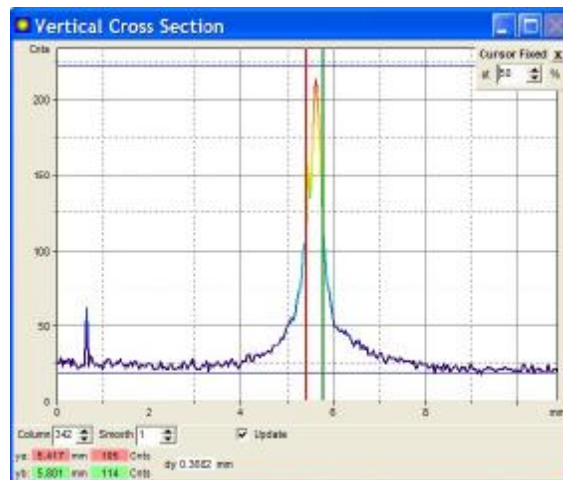
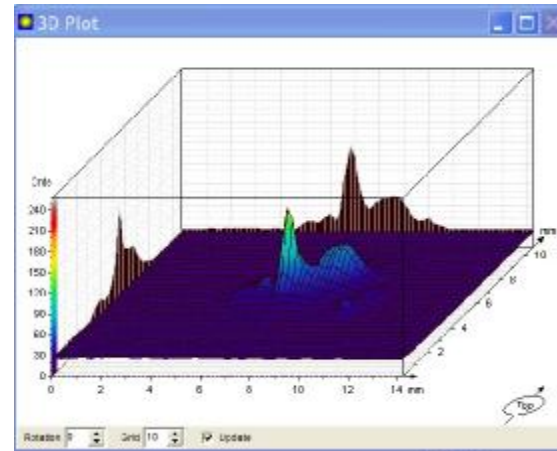
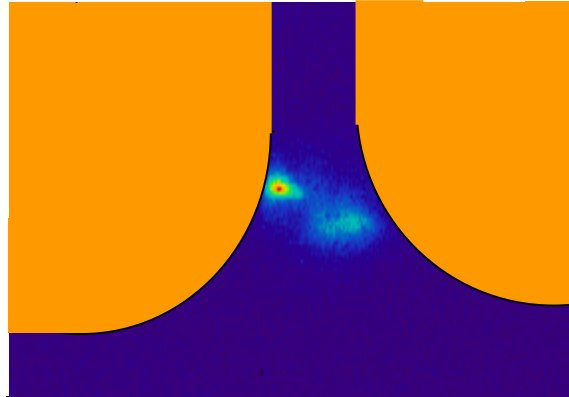


Photo of EUV emission from the plasma and pulse profile without pre-pulse.
Input energy 8,5 J, K=30%, pinch size 0,37 mm x 0,53 mm

Sn RDE source design 2

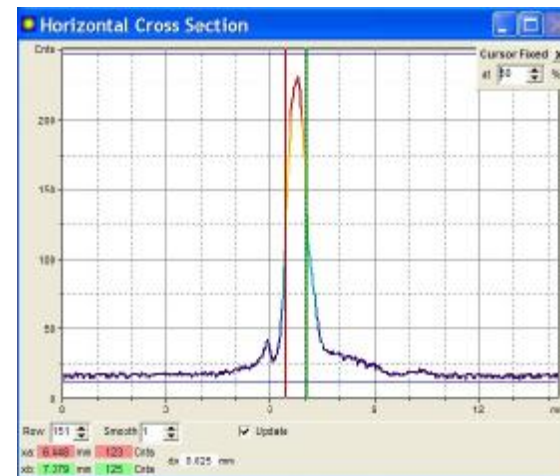
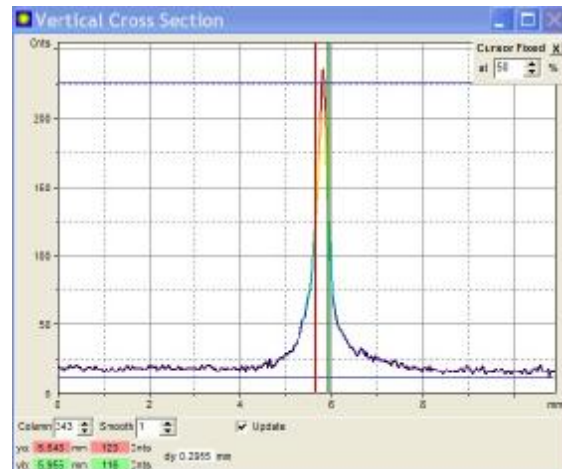
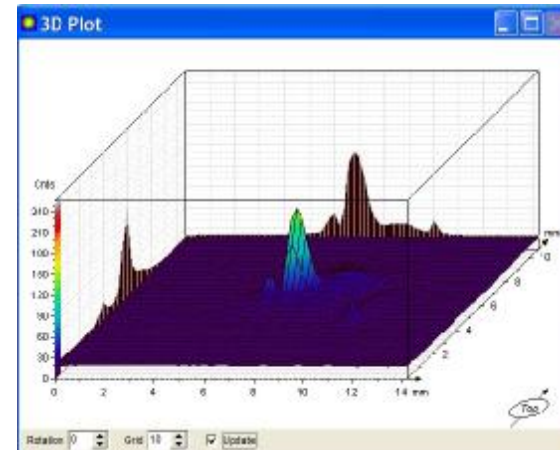
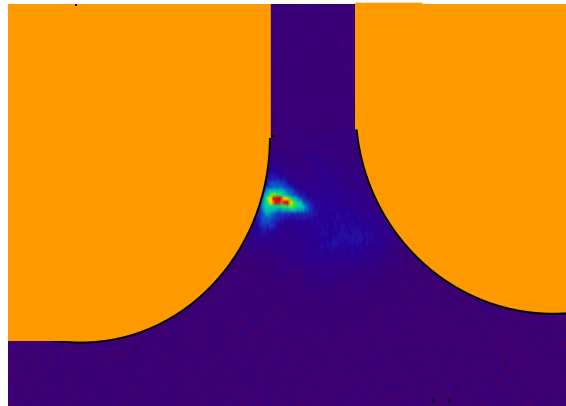
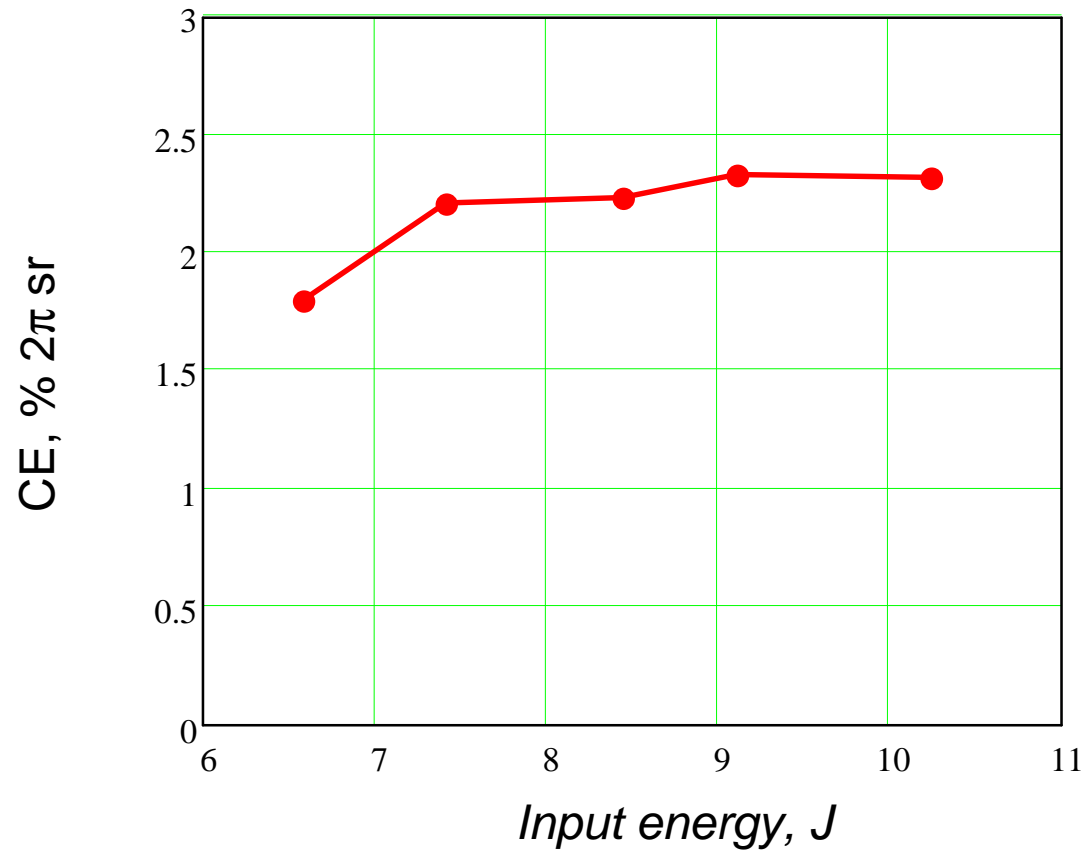


Photo of EUV emission from the plasma and pulse profile with pre-pulse.
Input energy 8,5 J, K=69%, pinch size 0,29 mm x 0,62 mm

Sn RDE source design 2

Pulse power system with a recuperation



Dependence of conversion efficiency on the input energy

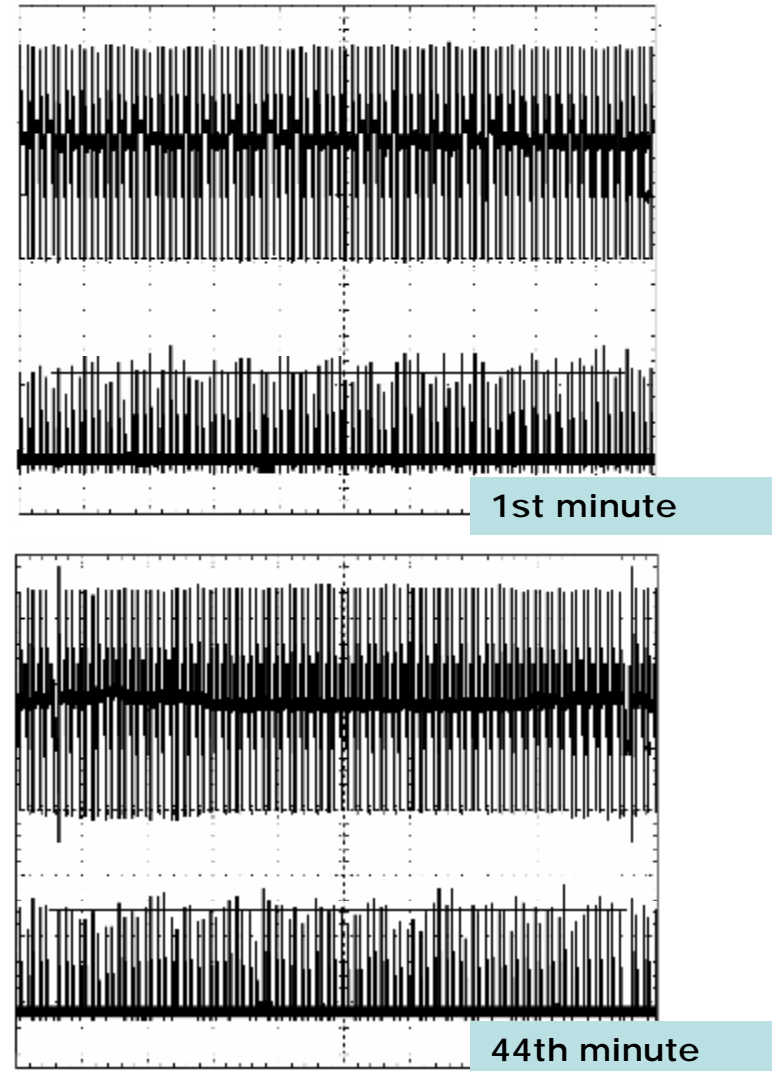
Sn RDE source design 2

Continuous operation with Nd:YAG laser AO8

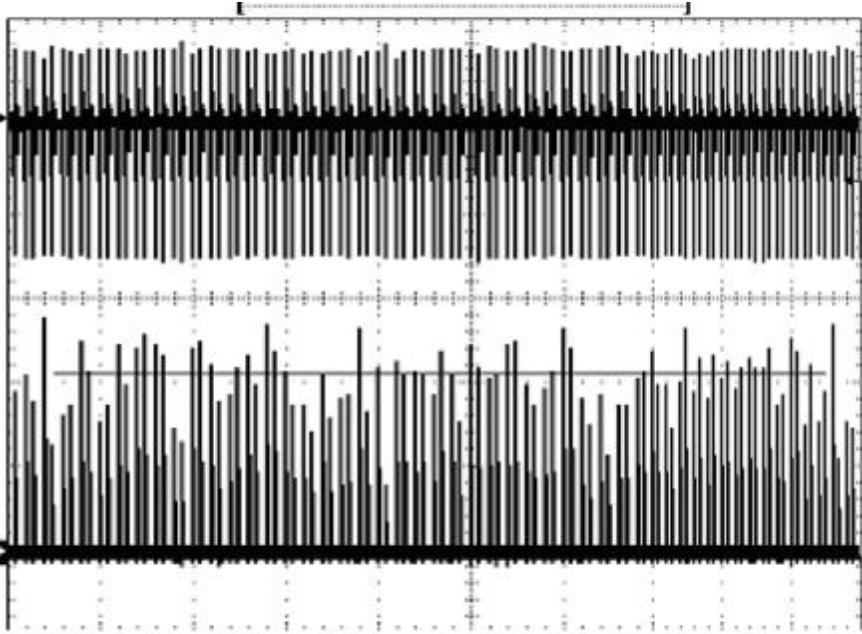
EUV power: $180 \text{ mJ} \times 2 \text{ kHz} = 360 \text{ W} / 2\pi$
at input power: $9 \text{ J} \times 2 \text{ kHz} = 18 \text{ kW}$
EUV signal does not decrease during
1 hour of source operation.

In the long-term experiment with input power $\sim 22.5 \text{ kW}$ at 2.5 kHz after 3 minutes of the experiment onset the stainless-steel lateral upper faces of the baths, located in the region of plasma emission, began to melt.

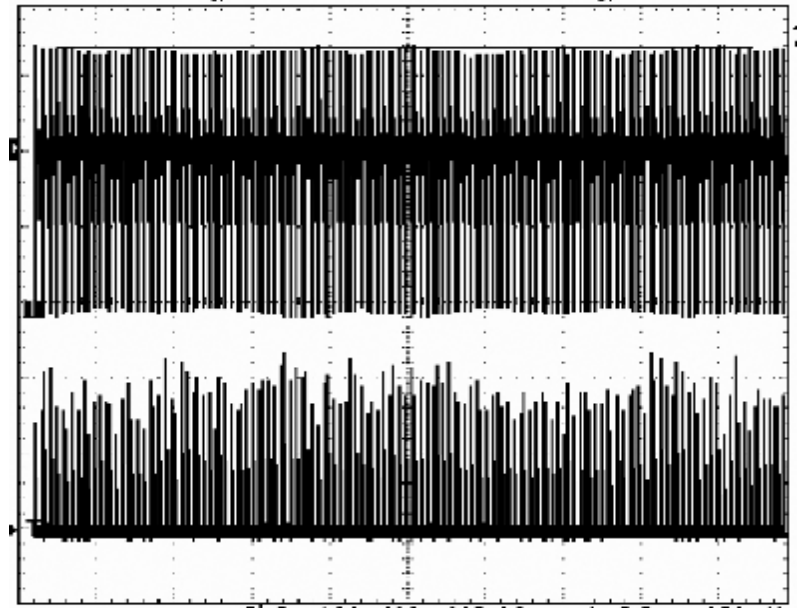
This circumstance determined the short time ($\sim 10 \text{ s}$) of source operation in the subsequent experimental study of the possibility of increasing input power.



Sn RDE source design 2



Input power 45 kW at 5 kHz

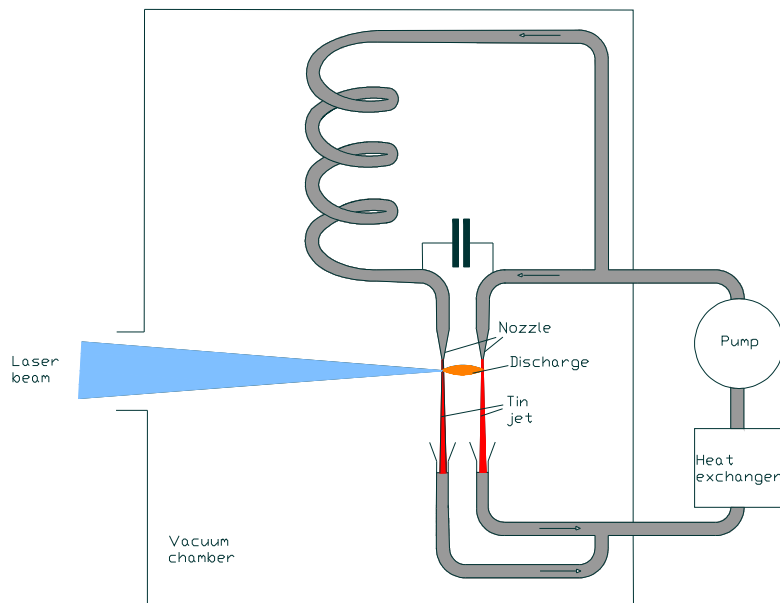


Input power 63 kW at 7 kHz

1 kW EUV in band power in 2p have been achieved with input power 63 kW at 7 kHz

Discharge between two liquid metal jet electrodes as EUV source

New type of discharge between two liquid metallic alloy jets serving as electrodes was proposed by Koshlev" group at Institute of Spectroscopy RAS as powerful source of VUV and specifically EUV radiation. It is expected that the proposed scheme is able to dissipate up to 200 kW of electrical power.



We think new source design will be more simple then other



Set-up for investigation EUV sources on the base discharge between two liquid metal jet electrodes at TRINITI

Conclusion

Specific features of EUV emission in discharge between rotating disk electrodes in tin vapour were investigated.

The results of numerical simulation of the discharge and EUV light generation and their comparison with the experimental data make more clear the dynamics of formation of the EUV-emitting plasma region.

It was shown that the source operates continuously and stably with up to 360 W EUV in band power in 2π .

In the short-term (10 s) regime 1 kW EUV in band power in 2π was obtained with input power of 63 kW at pulse repetition rate ~ 7 kHz.

We believe, next improvements, for example, the development of an electrode configuration based on heat-resistant metals, using more power pulse power system, will make it possible to implement continuous operation of the source with kilowatt level of EUV power required for HVM tools.